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Solar Cell Radiation Response Near the Interface of Different Atomic Number Materials

E.A. BURKE
J.R. CAPPELLI
L.F. LOWE
J.A. WALL

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E.A. Burke L.F. Lowe
J.R. Cappelli J.A. Wall

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13. ABSTRACT

The response of Co-60 irradiated N/P silicon solar cells was measured as a function of the atomic number of the medium adjacent to the cell and the direction of the gamma ray beam. The interpositioning of various thicknesses of aluminum between the adjacent material and the cell had the effect of moving the cell to various locations in an approximate monoatomic numbered medium. With this technique, the solar cell response was determined at various distances from the interface for gold and beryllium. When compared with predictions based upon ionization chamber measurements of dose perturbations in aluminum, the results showed agreement within five percent. Ionization chamber data were then used to estimate the influence of various base contact materials. The directional effect is greatest for the case where gold is used for the contacts. For this case, the solar cell response with the beam entering the cell face is 40 percent greater than when it enters the base. The situation is reversed for beryllium contacts which produce a response that is 17 percent greater when the beam enters through the base.

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Abstract

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Solar Cell Radiation Response Near the Interface of Different Atomic Number Materials

1. INTRODUCTION

The prediction of solid state device response to ionizing radiation requires a knowledge of the energy absorbed (the dose or dose rate) in active regions of the device. If the device is adjacent to materials (packaging or structural supports) with atomic numbers different from the device material and if the primary radiation produces electrons with ranges comparable to device dimensions, ionization chamber studies indicate that the energy deposited can vary significantly from that absorbed in the absence of surrounding materials. Methods commonly used for predicting the dose frequently neglect the possible effect of adjacent materials. Similarly, the materials, dimensions, and encapsulation of dosimeters rarely correspond to the test specimen, resulting in misleading experimental measurements. Little is known concerning the nature and magnitude of the dose perturbations produced and, as a result, theoretical predictions have not been adequately tested.

The greatest amount of work on the problem of dose perturbations at interfaces has been done in the interest of the biological effects of radiation, with particular concern in the enhanced dose in soft tissue adjacent to bone under X-irradiation. Experimental as well as theoretical work on this problem has been reviewed by Spiers (1969).

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In view of the large differences in the photoelectric cross sections for elements of different atomic number and the resultant large difference in the deposited energy, it is not surprising to find dose perturbations near interfaces at X-ray energies. At gamma ray energies where the Compton cross section is dominant, energy deposition varies relatively little from one material to another and small perturbations may be expected.

The fact that significant changes in the dose can occur at gamma ray energies was first pointed out by Dutreix et al (1966) and recently examined for typical device materials exposed to Co-60 gamma radiation by Wall and Burke (1970). Energy deposition profiles in aluminum adjacent to gold are shown in Figure 1. The data, obtained with a multiple cavity parallel plate ionization chamber technique show that the dose in aluminum is enhanced when the gamma beam penetrates the aluminum before entering the gold. However, the dose is actually reduced below equilibrium value for aluminum when the gamma beam is reversed. Further, there is a strong directional effect. This effect is noticeable at a distance of 200 mg/cm^2 away from the boundary, which means that it extends over typical device dimensions. For lower atomic number materials, the effect is similar but somewhat reduced as shown in Figure 2. Notice, however, that the minimum in the dose profile reaches its lowest values for materials of intermediate atomic numbers, such as molybdenum. It has also been found (Wall and Burke, 1970) that beryllium or carbon adjacent to aluminum reverses the effect, that is, the aluminum dose is enhanced when the gamma beam penetrates the beryllium first, and reduced for the opposite direction. Further, it has been found that micron layers of high atomic number materials produce a readily observable effect as shown in Figure 3.

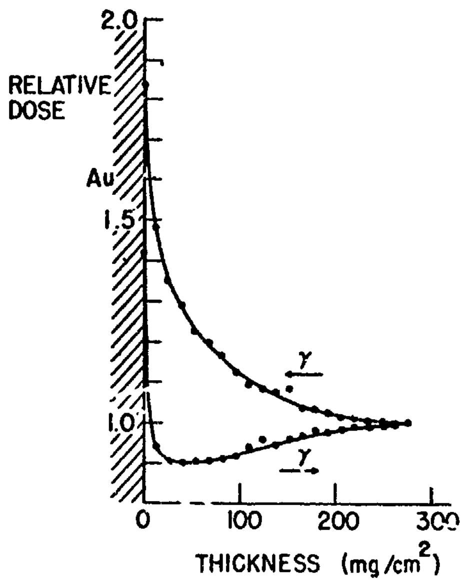

Figure 1. Air Ionization Measurements of the Relative Dose in Aluminum Next to Gold. Arrows indicate the direction of the gamma beam.

It is important to note that the results described were obtained with ionization chambers. We must be cautious in assuming that other phenomena, such as electron-hole pair production in semiconductors will behave in the same way in the transition zone near an interface. With the application of ion chamber data to

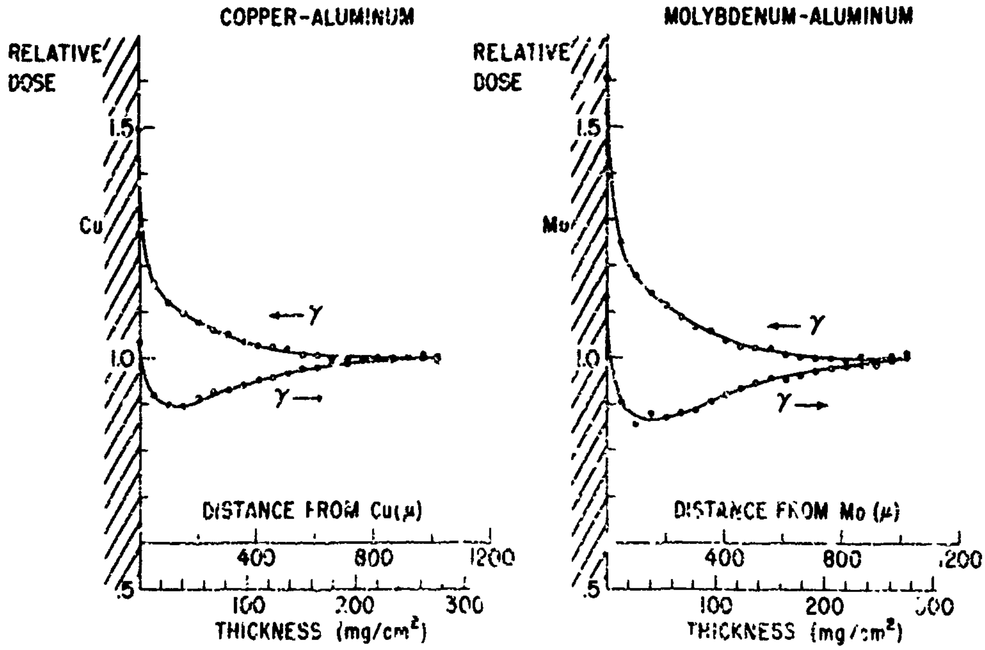

Figure 2. Air Ionization Measurements of the Relative Dose in Aluminum Next to Copper and Molybdenum

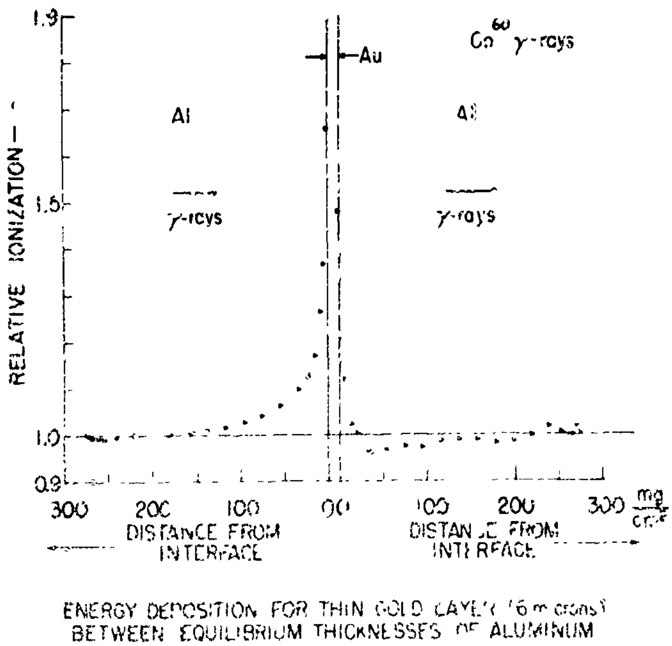

Figure 3. Air Ionization Measurements of Dose Perturbations Near a Thin Gold Film

solid state devices, it is shown that the response of the latter can be predicted from the former. This was the primary objective of the work reported here.

Solar cells were selected for examining the possibility of predicting device response. The interface conditions were similar to those studied with ionization chambers. The results indicated that ionization chamber data could be employed for the prediction of device response. Calculations were then carried out for solar cells with base contacts of several different materials.

2. EXPERIMENTAL PROCEDURE

The devices employed were 1×2 cm, N/P silicon solar cells with 0.5 μm junction depth and a 2.5 Ωcm base resistivity. The diffusion length of minority carriers in the base was determined by exposing the cells encapsulated in aluminum (to establish equilibrium, dose conditions) to a Co-60 gamma source and by measuring the short circuit current. The dose rate was established with a calibrated ionization chamber and the minority carrier production rate calculated, assuming the requirement of 3.6 eV for production of an electron-hole pair (Klein, 1968). Typical diffusion lengths for undamaged cells were in the vicinity of 140 μm.

The sample holder employed in the solar cell exposure is shown in Figure 4. The cell was mounted in a recessed aluminum plate whose thickness exceeded the range of the highest energy electrons generated by Co-60 gamma radiation. In the

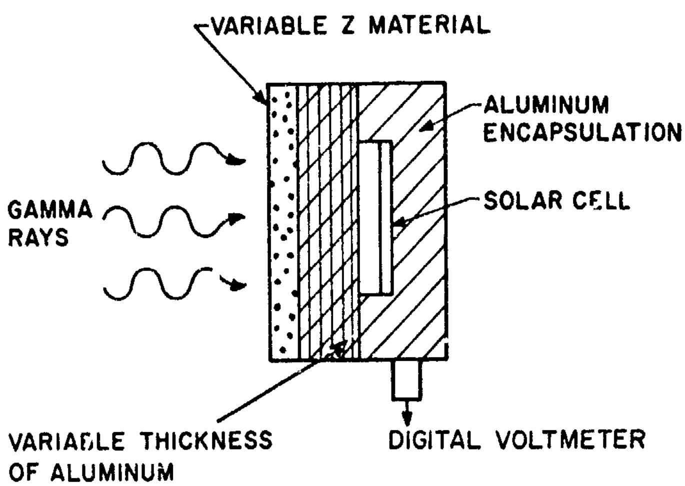

Figure 4. Experimental Configuration Used in Solar Cell Measurements

experiments reported here, the base contact was adjacent to the aluminum plate. Aluminum foils of variable thickness could be placed between the face of the cell and the gold or beryllium plates used in the interface studies. Rotation of the sample mount through 180° permitted the response to be determined for both beam directions.

A 15 kilocurie Co-60 source was employed in the irradiations. Both collimated and uncollimated photon beams yielded the same results within the uncertainty of the measurements. In order to normalize the data, the cell response was measured with aluminum, replacing the gold or beryllium end plate.

3. COMPARISON OF CELL RESPONSE WITH IONIZATION CHAMBER RESULTS

The short circuit current as a function of aluminum foil thickness was normalized to the current observed with the cell completely encapsulated in aluminum. Results are shown for both gold and beryllium end plates and for two beam directions (Figures 5 and 6). As can be seen, the response is qualitatively similar to the ion chamber results. The difference can be attributed to the solar cell thickness (0.038 cm) which represents a significant fraction of the distance over which the dose perturbation occurs. If the ion chamber results are a true indication of the dose rate, the carrier generation rate will not be uniform throughout the cell. We can make a quantitative comparison by adopting an approach similar to that used in calculating the spectral response of solar cells.

For electrons in the p-type base, the form of the continuity equation applicable is

$$G_n - U_n + \frac{1}{q}\,\mathrm{div}\,\vec{J}_n = \frac{\partial n}{\partial t}\ , \tag{1}$$

where n is the excess minority carrier concentration in the base, $\vec{J}_n$ the current density, G_n and U_n re the minority carrier generation and recombination rates, and q is the charge on an electron. For steady-state conditions, zero electric fields, low injection and one dimensional geometry, Eq. (1) simplifies to

$$G_n - \frac{n}{\tau_n} = -D_n\,\frac{\partial^2 n}{\partial x^2}\ , \tag{2}$$

where τ_n is the lifetime of minority carriers and D_n the diffusion coefficient. The normalized ionization chamber data can be fitted with an exponential series to within a few percent. It we assume that the generation rate is given by the same function, we have

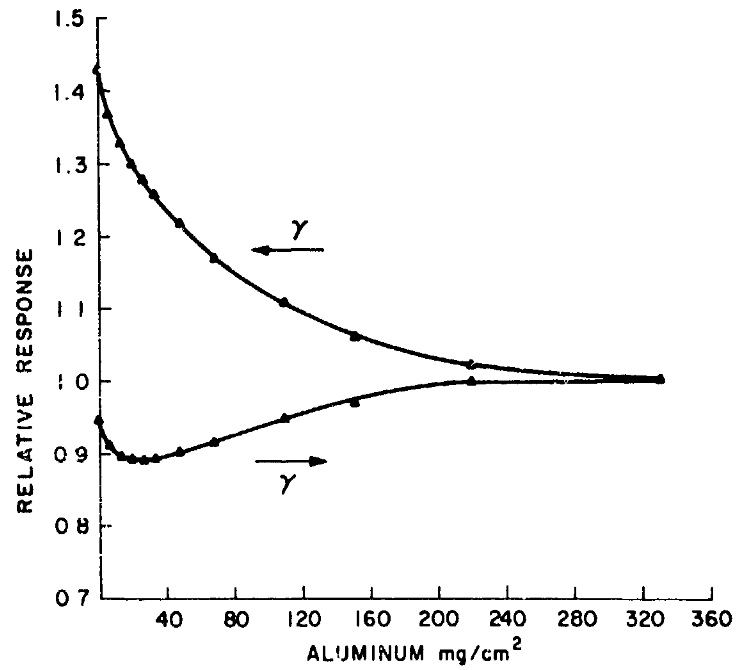

Figure 5. Measured Solar Cell Response Near an Au-Al Interface

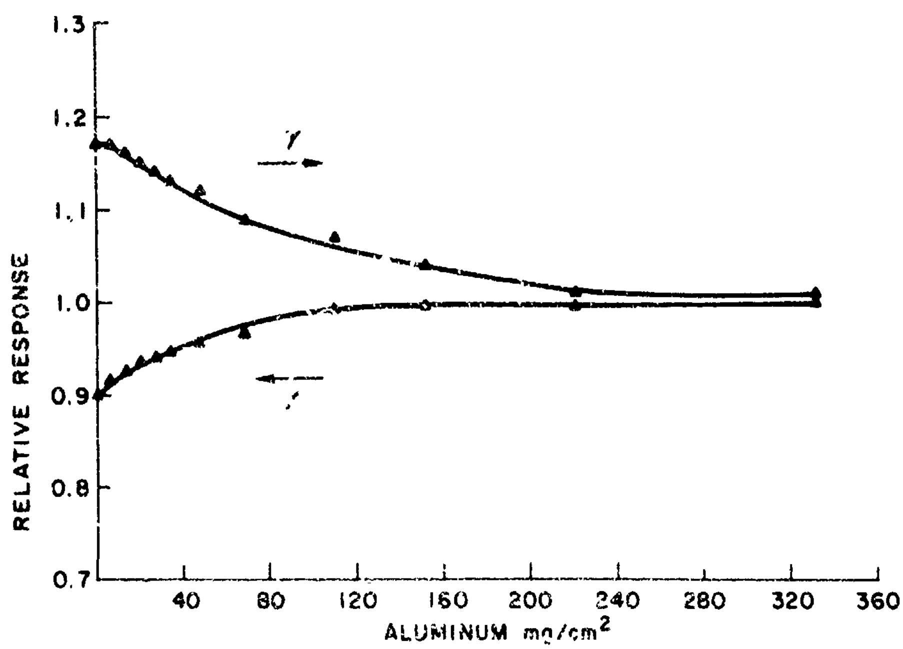

Figure 6. Measured Solar Cell Response Near a Be-Al Interface

$$G_n = G_o \sum_m A_m e^{-\alpha_m (x+x_1)} , \tag{3}$$

where x_1 is the thickness of aluminum between the end plate and face of the cell, and x any point within the cell as measured from the cell face. The values of the coefficients for beryllium, copper, and gold are given in Table 1. The solution to Eq. (2) is

$$n = C_1 e^{x/L} + C_2 e^{-x/L} + G_o \sum_m B_m e^{-\alpha_m (x_1+x)} , \tag{4}$$

where

$$B_m = \frac{A_m}{D_n} \left(\frac{1}{L_n^2} - \alpha_m^2 \right)^{-1} , \tag{5}$$

and L_n is the diffusion length which is equal to $\sqrt{\tau_n D_n}$. If we assume that the excess minority carrier concentration is zero at the junction and at the base contact, that is, $n = 0$ at $x = \ell$ and $x = b$, then

$$C_1 = \left(e^{b-\ell/L} - e^{\ell-b/L} \right)^{-1} \times \tag{6}$$
$$G_o \sum_m B_m \left(e^{-\alpha_m (x_1+\ell)-b/L} - e^{-\alpha_m (x_1+b)-\ell/L} \right)$$

and

$$C_2 = -\left(e^{b-\ell/L} - e^{\ell-b/L} \right)^{-1} \times \tag{7}$$
$$G_o \sum_m B_m \left(e^{-\alpha_m (x_1+\ell)+b/L} - e^{-\alpha_m (x_1+b)-\ell/L} \right) .$$

The diffusion current from the base is given by

$$J = q D_n \left. \frac{dn}{dx} \right|_{x=\ell} . \tag{8}$$

When $\ell \ll L$ the ratio of the diffusion current $J(x_1)$ to that for uniform ionization J_o, is given by

$$\frac{J(b)}{J_c} = \frac{D_n}{L^2} \frac{1}{(\beta+\alpha)} \times$$

$$\sum_m B_m e^{-\alpha_m (x_1 + \ell)} \left[\beta - \alpha e^{-\alpha_m (b - \ell)} - \alpha_m L\right] , \qquad (9)$$

where

$\beta = \coth (b/L)$

$\alpha = \mathrm{csch}\ (b/L)$.

The results obtained from Eq. (9) are compared with the normalized solar cell response of a cell that had a measured diffusion length of $140 \pm 15\ \mu m$ (Figures 7 and 8). For gold and beryllium the normalized results agree within a few percent. For these cases, the calculated relative sensitivity of the result to the diffusion length is shown in Figures 9 and 10.

Table 1. Coefficients for the Empirical Fit to Ionization Chamber Measurements of Energy Deposition Profiles in Aluminum Adjacent to Beryllium, Copper, and Gold*

Beam Direction High Z → Low Z						
End Plate	A_2	A_3	A_4	α_2	α_3	α_4
Be	-0.159	-0.075	0	0.0213	0.137	0
Cu	-0.183	0.192	0	0.0094	0.0749	0
Au	-0.262	0.255	0.284	0.0097	0.0408	0.351
Beam Direction Low Z → High Z						
End Plate	A_2	A_3	A_4	α_2	α_3	α_4
Be	0.283	-0.836	0	0.0122	0.0325	0
Cu	0.204	0.293	0	0.0172	0.334	0
Au	0.526	0.231	0.249	0.0144	0.0998	0.346

*Relative Dose $= \sum_m A_m e^{-\alpha_m x}$

In all cases $A_1 = 1.0 \quad \alpha_1 = 0$

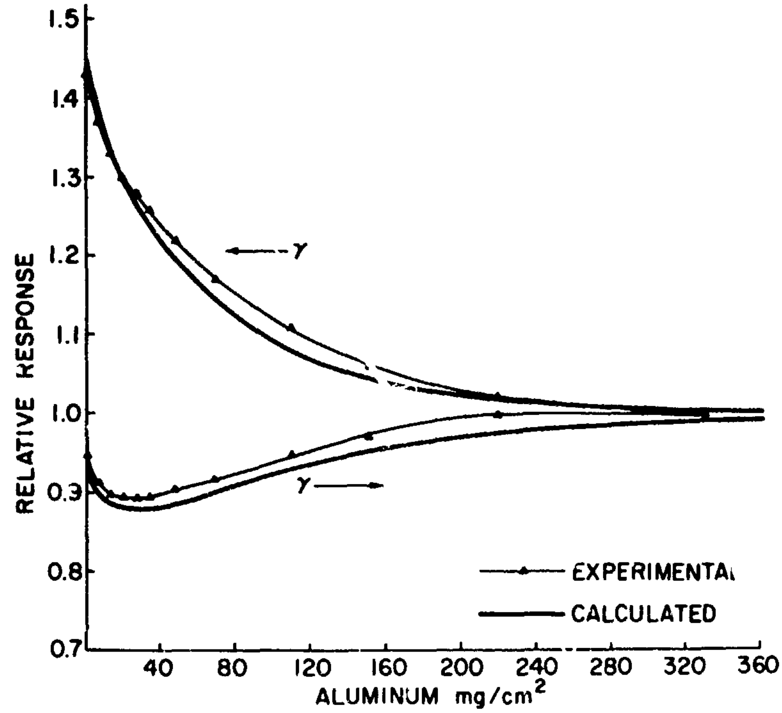

Figure 7. Comparison of Measured Solar Cell Response Near an Au-Al Interface and Calculations Based Upon Ionization Chamber Measurements

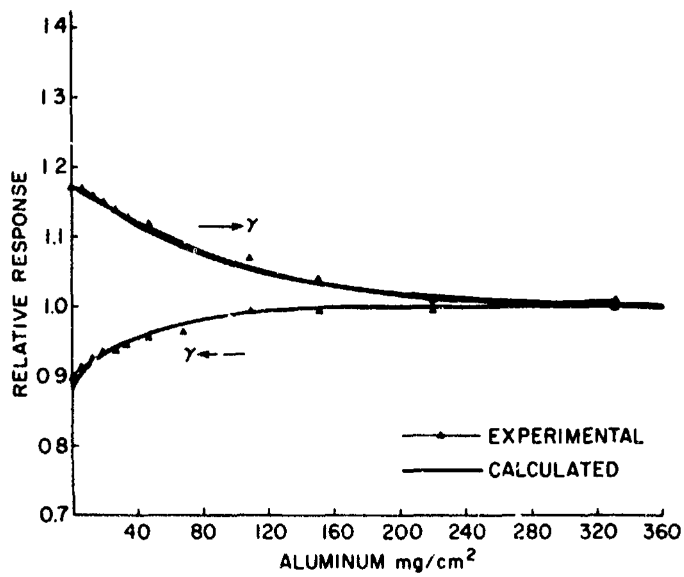

Figure 8. Comparison of Measured Solar Cell Response Near a Be-Al Interface and Calculations Based Upon Ionization Chamber Measurements

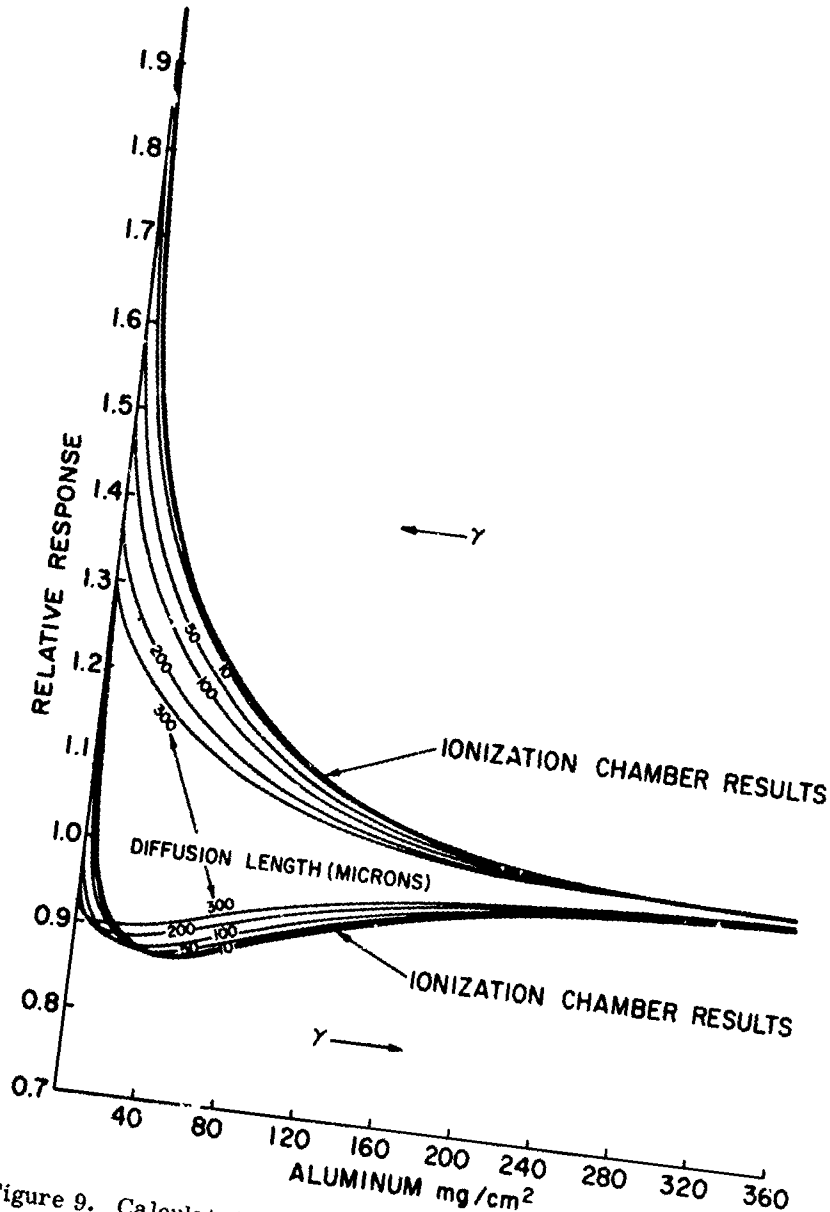

Figure 9. Calculated Influence of Diffusion Length Upon Solar Cell Response Near an Au-Al Interface

4. CALCULATED SOLAR CELL RESPONSE FOR VARIOUS BASE MATERIALS

Since calculations of solar cell response based upon ionization chamber data agreed well with measurements when the interface was adjacent to the cell face, they were extended to the more realistic situation where the material was

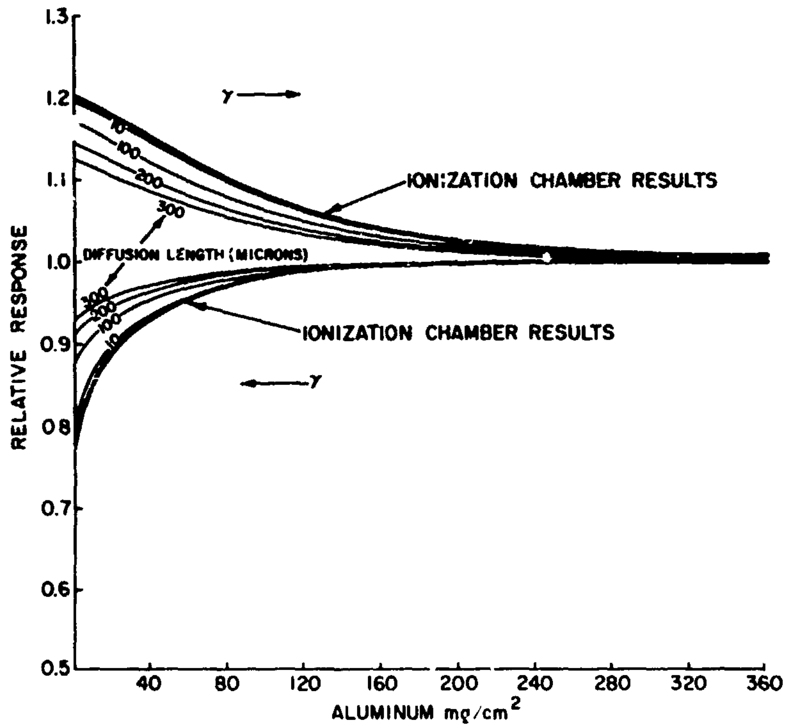

Figure 10. Calculated Influence of Diffusion Length Upon Solar Cell Response Near a Be-Al Interface

adjacent to the base contact. This requires a modification of Eq. (9) as follows:

$$\frac{J(x)}{J_o} = \frac{D_n}{L^2} \frac{1}{(\beta+\alpha)} \times$$

$$\sum_m B_m e^{-\alpha_m (x_1+b-\ell)} \left[\beta - \alpha e^{-\alpha_m (\ell-b)} -\alpha_m L\right] \qquad (10)$$

In this case, x_1 is the thickness of aluminum interposed between the base contact and the interface. All other quantities are the same as those employed in Eq. (9).

Calculations based on Eq. (10) are shown in Figures 11 to 14. As might be expected, the perturbation is largest for a thick (> 0.02 cm) gold base. When the beam enters through the cell and leaves from the gold, the response is 23 percent larger than it would be for an aluminum base contact. The reversed beam yields a result which is 12 percent lower than it would be for aluminum. Even 6 μm of gold produces an effect. The influence of copper, as well as the influence of

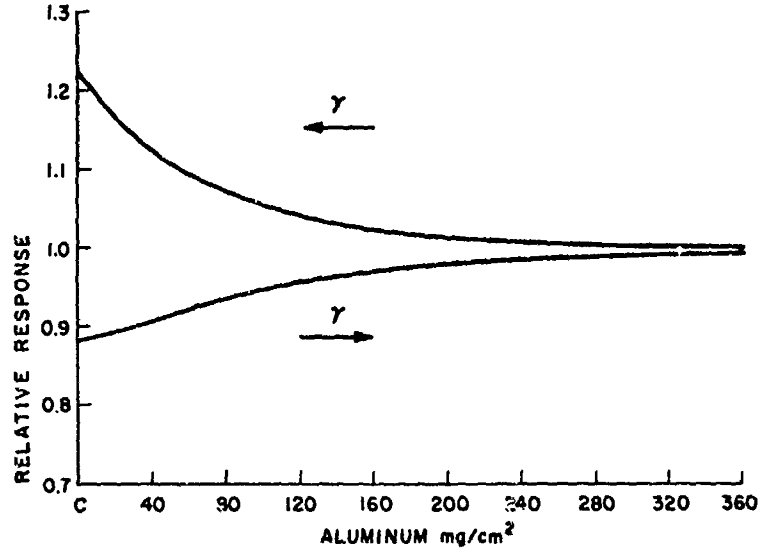

Figure 11. Calculated Response With the Au-Al Interface Near the Base Contact. The thickness of aluminum indicated lies between the gold and the base. Arrows indicate the beam direction relative to the cell face.

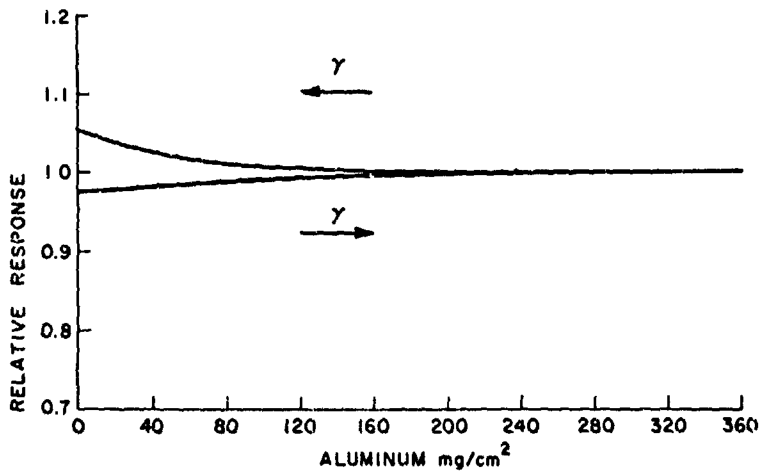

Figure 12. Calculated Response for a Thin Gold Film Near the Base Contact

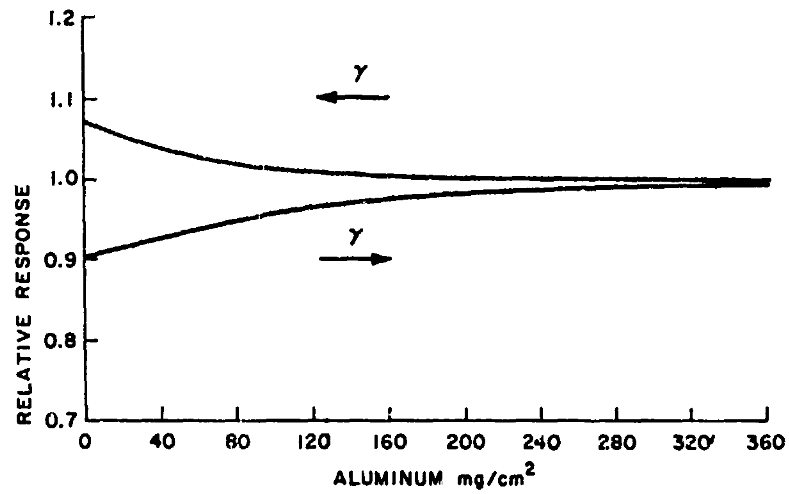

Figure 13. Calculated Response for a Cu-Al Interface Near the Base

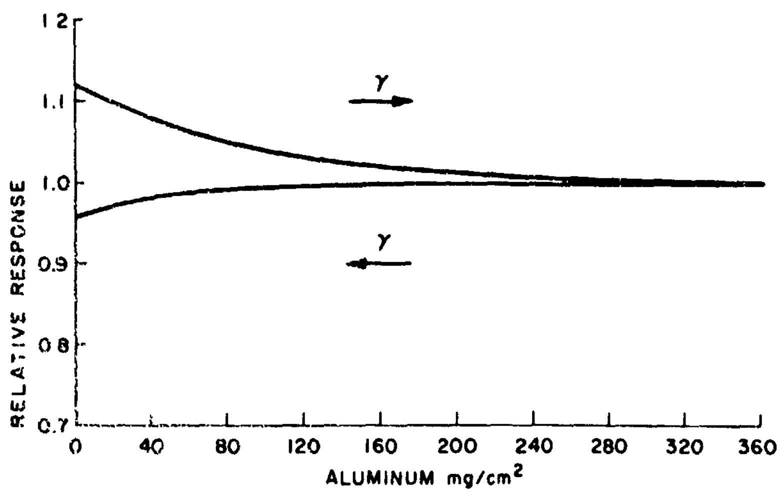

Figure 14. Calculated Response With a Be-Al Interface Near the Base Contact

beryllium, is smaller than for thick gold but readily noticeable. It is interesting to note that when the beam enters through the beryllium contact the response is approximately 12 percent greater than it would be for an aluminum base contact. Low atomic number materials can enhance the response if traversed by the beam before entering the device.

5. SUMMARY

Ionization chamber measurements of dose perturbations in aluminum adjacent to gold and beryllium can be used to predict the response of silicon solar cells near the same materials. The influence of gold, copper, and beryllium base contacts has been calculated for N/P silicon solar cells exposed to Co-60 gamma rays. Strong directional effects are evident in all cases. Further, the response can be enhanced by both high and low atomic number materials, depending upon the direction of the gamma beam. For the cells examined here, the response as a function of beam direction varied as much as 40 percent. Ionization chamber measurements indicate that at Co-60 gamma energies (1.25 MeV), the interface effects could be as large as a factor of two.

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